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AND

Pressures Lower than Atmospheric

Dissertation
Submitted to the Board of University Studies
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in Conformity with the Requirements for the
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PRESS OF
THE NEW ERA PRINTING COMPANY
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[Reprinted from the PHYSICAL REVIEW, N.S., Vol. V, No. 4, April, 1915.]

THE CORONA IN AIR AT CONTINUOUS POTENTIALS AND PRESSURES LOWER THAN ATMOSPHERIC.

BY DONALD MACKENZIE.

SINCE the practical importance of the corona discharge was first realized, the subject has been extensively investigated both in this country and abroad.

The general agreement among observers is that the corona-forming voltage is independent of the material of the discharging conductor and of the humidity of the air; that the critical surface-intensity is greater for smaller wires; that increased temperature or decreased gas pressure decreases the critical voltage; and finally, that the onset of the phenomenon is not affected by the antecedent ionization near the wire.

It was with a view to examine the continuous potential corona at low pressures and so to test the extension of the empirical laws found for the alternating corona that the work here reported was begun. In this laboratory at the present time the only available source of direct current at high potential is a battery of 500-volt, 0.1 kilowatt generators driven by a direct current motor. These generators are separately excited from a lighting circuit, which also furnishes power to the motor; this makes the control of voltage very difficult, the fluctuations in the line voltage amounting at times to three or four per cent. Most of the irregularities of the points plotted for some of the curves are attributable to this condition. The speed control of the motor enables the generated voltage to be raised to more than 900 volts on each machine: at the beginning of the work five such generators were at hand, furnishing a potential of 4,000 volts and more, but two machines broke down before much progress had been made. This limited the total voltage to 2,700 volts, and so placed a regrettable restriction on the dimensions of the corona apparatus and the pressure range.

DESCRIPTION OF APPARATUS.

A diagram of the apparatus used is shown in Fig. 1. *A* is a large glass tube 10 cm. in diameter and 75 cm. long, inside of which is supported by hard rubber rings the brass cylinder *B*, 4.9 cm. in internal diameter and 61 cm. long. These rings are pierced with a number of holes to permit

free flow of air through all parts of the apparatus. The glass cylinder is closed at each end by brass plates, cemented on with a mixture of beeswax and rosin. In the center of each of these plates a hole is drilled, permitting the passage of the wire *C*, which is soldered at each end into bushings held by the nuts *DD*. In all cases it was easy to apply sufficient tension to hold the wire straight unless a large current was allowed to pass in the discharge.

The glass tube *A* is provided with three side tubes, two of which serve for the ground connection to the brass cylinder and for the pump connection respectively. The third side tube, the uppermost in the figure,

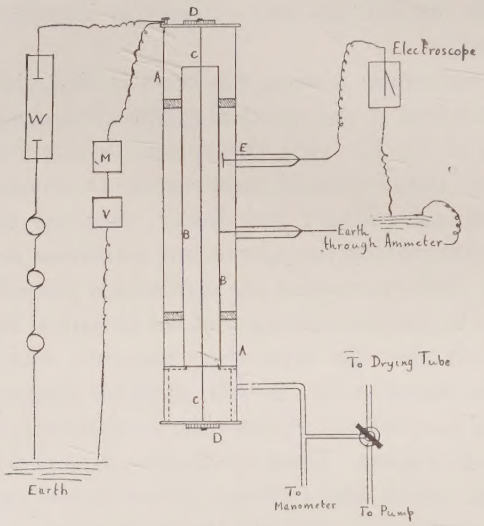

Fig. 1.

Diagram of corona apparatus.

supported another glass tube, sealed into it with sealing wax and drawn down at each end to hold a small brass rod screwing into a brass plate about 2 cm. in diameter. Connection to ground and to the brass rod just mentioned was by small platinum wires sealed directly into the glass tubes. The disk carried on the end of the brass rod *E* is curved parallel to the surface of the brass cylinder, and stands about a millimeter above it. Directly under the disk are a dozen or more small holes in the cylinder, through which charged particles may pass on their way out from the central wire, charging or discharging the electroscope to which the disk is connected.

The voltage of the three generators is applied to the apparatus over leads including the water resistance *W*, about 3 cm. in diameter and 75 cm. long, variable by varying the separation of platinum electrodes.

One end of the generators is connected thus to the brass plate closing the glass tube; the other end is earthed, as is the brass cylinder through a milliammeter or galvanometer. Reversal of wire polarity is effected by reversing the excitation of the generators. Measurement of voltage is by means of a Weston D.C. voltmeter V with a multiplier M, reading 150 volts when the wire potential is 3,000.

The apparatus is supported vertically on a table, from which it is insulated by porcelain blocks. To prevent the breaking of the ground connection by slipping of the corona tube, the latter is supported on a hollow wooden cylinder, the walls of which are turned very thin except at the top, where a ring supports the lower end of the brass tube. In immediate contact with the tube is a thin ring of hard rubber; this ring extends into the field no more than a millimeter, and in no case was any irregular behavior of the discharge caused by its presence.

In the upper brass plate are cut holes covered with glass windows. Above these is fixed a mirror permitting visual exploration of the space within the cylinder.

It was expected that a charged electroscope connected with the disk E would be affected by a discharge passing between the wire and the cylinder: a positive corona on the wire should discharge a negatively charged electroscope and vice versa. This expectation was justified: when the corona starts the gold-leaf drops instantaneously and there is no possibility of confusing this effect with a loss of charge due to atmospheric leak. As the voltage is raised, electrostatic induction brings about a partial fall of the gold-leaf: a negatively charged gold-leaf receives an induced positive charge in the presence of the positively charged wire, the corresponding negative charge appearing at the disk E. As long as the potential of the wire is constant the magnitude of the induced charge on the electroscope does not vary, and the definiteness of the observation is not diminished by this action.

The electroscope is charged statically, and the voltage gradually raised until the gold-leaf suddenly falls. The voltmeter is then read and the pressure recorded.

The wires used were carefully straightened by the electric current, except in the case of the larger wires, which were brass rods free from kinks. All were polished with fine emery and crocus cloth, and when put into the tube showed no sign of surface irregularity. Dust particles from the air settling on the wire are of no importance, since unless the wire is sticky they are driven off by electrostatic repulsion. This fact has been overlooked by most observers, who attribute irregular behavior of the corona to dirt which they suppose to have settled on the wire.

The most important step in setting up the apparatus is the centering of the wire in the brass cylinder. The method used is as follows: The end bushings pass through quarter inch holes in the end plates which allow sidewise displacement of the whole wire. When the nuts are tightened to give the tension considered suitable, a scale is placed under the apparatus lying horizontal on the table. The eye is held steady over the scale, which lies just parallel to the end of the brass cylinder. Placing the head at such a distance above the tube that the cylinder subtends at the eye a given number of scale divisions, say 2.5 in., it is possible to judge how far from center is the wire: if the tube covers 2.5 in. on the scale the wire should stand over the 1.25 in. division. If such is not the case, adjustment is made by moving the nut across the end plate, and the apparatus is then turned through 90 degrees to make a second adjustment at right angles to the first. Then the previous adjustment is re-examined and corrected if necessary, and the procedure repeated at the other end. The cylinder of wood at one end of the tube hides the wire, but by gently tapping the end plate opposite, the brass tube can be induced to move away from the wooden ring sufficiently far to permit centering. Then, when both ends are satisfactorily adjusted on the axis of the cylinder, the apparatus is ready for installation. It was found a simple matter to set the wire to 1/200 in.

When the tube has been set in place the air is exhausted by means of a Gaede pump and the space refilled with air drawn through a column of sulphuric acid to exclude moisture. This is repeated a number of times, and the apparatus left exhausted to allow leaks to manifest themselves. With the number of beeswax and rosin seals necessary, leaks could not absolutely be avoided, but they could usually be kept so slight that no alteration in the reading of the manometer could be detected in the time spent in making observations at any one point. When the leakage was faster than this, it was possible to estimate its magnitude and correct the pressures recorded. This occurred in only one case, which will be described later. The pressure was read on a closed mercury manometer connected immediately to the glass tube.

PRELIMINARY EXPERIMENTS.

The first experiments were made with large wires, 3/32 in. in diameter. The voltage then available was 4,000, and corona formed on such wires at a pressure of about 4 or 5 cm. At once a difference was noted in the positive and negative discharges. With the wire positive, the corona formed at a definite voltage and pressure, disappearing as soon as the voltage was lowered or the pressure raised by the smallest step that

could be made. With the wire negative, however, the discharge was of quite different form. At a given impressed voltage, no visible discharge passed until the pressure was lowered well below the value corresponding to the positive corona at the same potential. Finally, however, came on a discharge carrying a large current sufficient to burn out two 16-c.p. incandescent lamps in series in the ground connection. This discharge persisted after the voltage was lowered far below the initial value, and was not extinguished by a moderate increase in pressure. In fact, a discharge setting in, say at 3,500 volts and 4 cm. pressure, persisted up to a pressure of more than 26 cm. Increase in pressure was accompanied by an increase in the current flowing; even at low pressure sufficient heat-energy was liberated to make the glass tube uncomfortably warm.

The water resistance had not been used. It was then inserted in the high potential side in order to keep the current down to a value safe for the generators. On examining the discharge from the negative wire, it was seen to show the characteristic structure of the discharge in high vacua. The appearance will be described presently. Instead of a uniform glow along the whole wire as in the positive effect, the luminosity is confined to a small length of the negative wire.

With the large wires it was possible to obtain the positive corona at the lowest pressures attainable (from 1 to 2 mm.) but the negative corona never appeared: the discharge from the negative wire was always of the vacuum tube type. On removing the wire from the tube it was found deeply oxidized at the points where the vacuum tube discharge had existed.

This singularity is intimately associated with the size of the wire, as will appear from the experiments about to be described.

Final Results.

1. *The Positive Effect.*—All of the wires when positive to the tube form coronas at the lowest pressures to which the apparatus was evacuated. The discharge is a perfectly uniform and stable violet or bluish glow extending the whole length of the wire within the brass cylinder. Using the electroscope charged negatively, the gold-leaf is seen to fall sharply at a definite voltage, and keeping the pressure constant this value of voltage may be read any desired number of times. The recorded observations frequently show a disagreement of 20 volts among the readings repeated at a constant pressure: this disagreement is due not to any irregular behavior of the corona, but to the fluctuations in the voltage of the circuit supplying the generators and motor. In the time taken for the observer to note the fall of the gold leaf and thereafter read the voltage,

the voltmeter needle may move in one direction or another and then rest for several seconds. Variations of two or more scale divisions are not uncommon: these mean a variation of 40 to 50 volts in the potential of the wire. When two observers work simultaneously, one noting the electroscope and the other reading the voltmeter, these irregularities do not affect the observation.

It was invariably found for the larger wires that the onset of the visible corona accompanied the discharge of the electroscope. The corona is faint at onset and around small wires can be seen only with well rested eyes; however, it is seen whenever attempted under suitable conditions. Having once verified this expected result I relied thereafter upon the electroscope. With each wire the verification was repeated.

As the voltage is raised above that necessary to start the corona, the luminous sheath expands progressively, accompanied by an increase in the current making the latter readable on the milliammeter. With further increase in voltage a point is reached where the corona is unstable. A slight increase in voltage causes the corona, previously uniform over the whole length of the wire, to collapse to a vacuum tube discharge confined to a few millimeters. The instability of the corona at this transition point is shown by the fact that if the generator excitation and motor speed are kept at the appropriate value and the potential suddenly applied to the wire, corona forms for an instant and then collapses to the vacuum tube discharge. Refilling the tube with cool air and then exhausting anew lengthens the time taken for the change to 4 or 5 seconds. This lag could not definitely be determined owing to the variations in generator voltage. On the establishment of the vacuum tube discharge, the voltage drops 50 or 60 per cent. and simultaneously the current rises to many times its former value.

This form of discharge shows all the structure recognized in the vacuum tube discharge. The negative glow is a thin blue layer against the inner wall of the brass tube, separated from it by a narrow Crookes dark space. The positive column is a pink sheath enveloping (usually, but not always, completely) a centimeter or two of the wire, directly opposite the negative glow which does not go completely around the inner surface of the cylinder but covers an increasing circular extent of it with increasing voltage. Between the positive column and the negative glow is the Faraday dark space; at low currents (total voltage over corona tube and ballast resistance lowered) this space is invaded by the positive column, which becomes striated. Further lowering of the voltage causes the striations to become more distinct, and the positive column extends almost to the point of meeting the negative glow; the latter is greatly

diminished in extent and brilliancy. At last, just as the Faraday dark space seems to be completely eliminated, the discharge ceases. The same sequence of phenomena is seen when the pressure is allowed to increase. After cessation of the discharge the voltage between the wire and tube rises to the value appropriate to an inactive field.

Increasing the total voltage increases the current carried; the voltage on the tube and wire slowly decreases. Decreasing total voltage decreases the current at the same time that the tube-wire voltage gradually increases.

2. *The Negative Effect.*—For the larger wires used in my experiments the negative corona is not obtainable: the first detectable discharge is the vacuum tube discharge. For the smaller wires the case is different. At the lowest pressures the vacuum tube discharge is the only one obtainable. At higher pressures the negative corona appears, expands with increase of voltage above the critical value, and gives place to the negative vacuum tube discharge at a transition point determined, as in the positive effect, by the pressure and the wire diameter. After the vacuum tube discharge has been established the current and tube-wire voltage vary as in the positive effect. The cessation of the discharge is after the same sequence of changes in the two cases.

The negative corona is never a uniform sheath like the positive. It is grouped about bright blue points set at intervals along the wire; these blue points are surrounded by reddish streamers, and increase in number as the voltage increases. With decreasing voltage the blue points are the last to disappear: they persist at a voltage lower than that at which they form.[1]

After transition, the structure of the discharge is the same as the positive vacuum-tube discharge, but reversed: next to the wire is the Crookes dark space surrounded by the negative glow, cylindrical in form; then comes the Faraday dark space and after it the positive column flat against the surface of the tube.

The negative glow may appear outside the uniform field, at the very end of the wire—the positive column collecting in a restricted area at the edge of the brass tube. The discharge may start in the interior and climb up more or less rapidly to the end of the wire. This is probably due to convection currents, set up even in rarefied air by the very hot discharge. This explanation is suggested by the fact that if the voltage is suddenly removed and reapplied, the renewed discharge prefers points

[1] Since these observations were made, experiments by Farwell have shown that the negative corona is invariably that described above, and that the number of the blue points on the wire is characteristic of the voltage. Farwell, PHYS. REV., 4, 2d Series, 31–39, 1914.

which have just previously been discharging. It is reasonable to suppose that the air in this neighborhood is in a favorable condition to initiate the discharge, being adjacent to the most highly heated portion of the wire. Convection currents raise this hot air, making conditions less suitable at the lower end and more so at the upper end of the existing discharge column.

The energy of the discharge is sufficient to heat to redness the wire and partially to oxidize the wall of the tube: after prolonged discharge a green color is seen in the field. In both positive and negative effects at very low pressures (for this apparatus) the Crookes dark space is seen to lie over a negative layer. This luminosity adjacent to the cathode, accompanying the ionization of the gas by the canal rays, is more readily recognized at low pressures because of the greater length of the Crookes dark space.

DESCRIPTION OF OBSERVATIONS.

The observations at each point were considered satisfactory if no readings of the voltmeter differed from the mean by more than one half a volt; this variation was unavoidable because of fluctuations. The multiplier ratio being 20 to 1, this means that a disagreement of 10 volts was considered tolerable. The accuracy of the observations may be judged from the following table, showing some of the readings for the negative corona on a nickel wire, diameter 0.063 cm.:

Pressure in mm.	Voltmeter Readings.	Voltage.	Pressure in mm.	Volmeter Readings.	Voltage.
69.8	124.0	2,480	56.5	110.0	2,200
	123.8	2,476		110.0	2,200
	123.0	2,460		110.0	2,200
	124.0	2,480		110.0	2,200
62.5	116.5	2,330	48.2	101.0	2,020
	117.5	2,350		100.0	2,000
	117.0	2,340		100.0	2,000
				101.0	2,020

Wires of diameter 0.165 cm., 0.157 cm., 0.107 cm. and 0.063 cm. were all investigated using the electroscope as a detector of the onset of the corona. For the negative effect when no corona can be formed, visual observations were relied on: the behavior of the electroscope is irregular when the tube is sustaining a vacuum tube discharge unless the region involved lies directly under the disk E: in this event the positively charged electroscope is immediately discharged and then receives a negative charge.

When associated with the smallest wire, 0.042 cm. in diameter, the electroscope gave evidence of an ionization current unaccompanied by luminosity. At pressures even higher than one-half an atmosphere, the charged wire had an influence on the electroscope. Several electroscopes

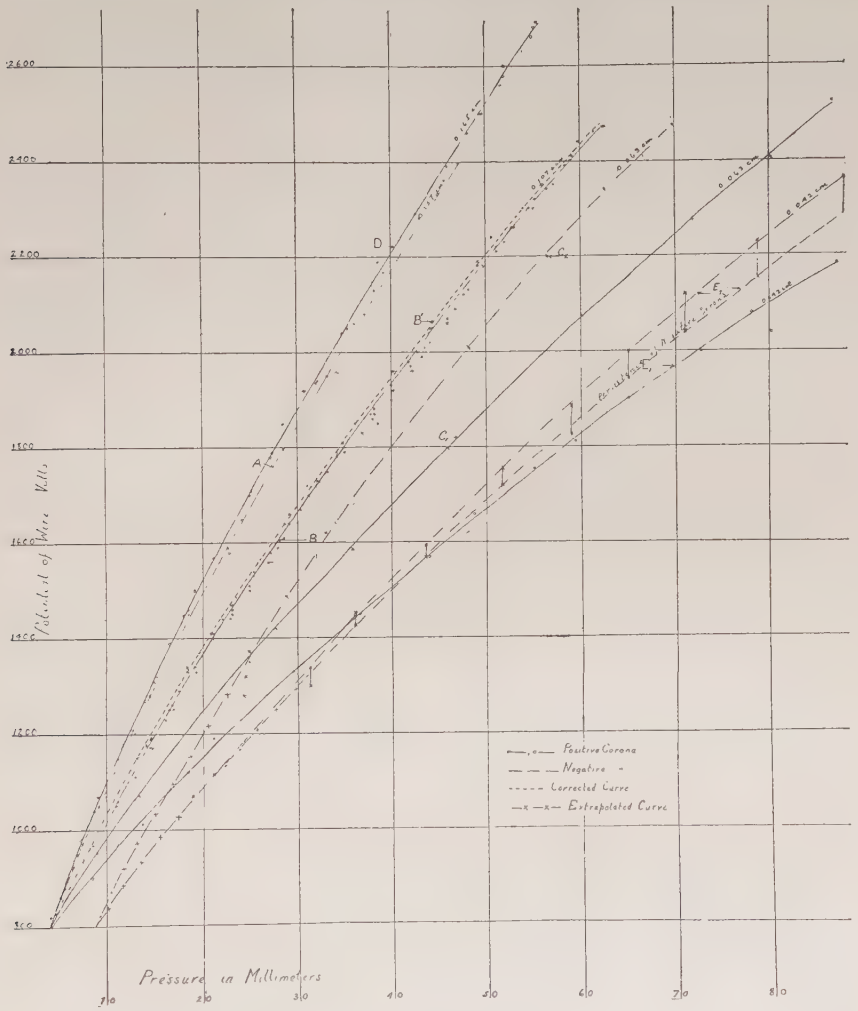

Fig. 2.

Corona-forming voltage. Diameters: A, 0.157 cm. +; B, 0.107 cm. +; B^1 is B corrected or leak; C_1, 0.063 cm. +; C_2, 0.063 cm. −; D, 0.165 cm. +; E_1, 0.042 cm. +; E_2, 0.042 cm. −.

of different form and size were tried, but all behaved in the same way: the electroscope charges spontaneously, the sign of the charge being positive when the wire is positive, negative when the wire is negative. The more sensitive electroscope charged until the gold leaf touched the

grounded case inclosing it, after which it fell back and the process repeated itself continuously.

Accordingly, the attempt to detect corona formation by the electroscope was given up for this size of wire, and in place of the milliammeter there was substituted a galvanometer, giving a deflection of one scale division for 7×10^{-6} amperes. The suitability of the galvanometer for this work (at least under these conditions) is shown by a comparison of curves A and E_1, Fig. 2.

Observations with the galvanometer are made as follows: The observer watches the galvanometer, at the same time slowly raising the voltage, and at the first perceptible deflection of the needle he reads the voltmeter. The experiment is repeated until the observer bècomes accustomed to noting very small deflections and has convinced himself that they occur at the same value of voltage each time, and are simultaneous with the appearance of the corona. He then proceeds with the same program as when using the electroscope.

Curve B, Fig. 2, is plotted from observations on a steel wire of diameter 0.107 cm. During these observations the leak of air into the apparatus was quite rapid and efforts to overcome it failed. Accordingly it was decided to let the apparatus leak and make observations in the following way: The electroscope was charged, the voltage raised until the gold-leaf fell, then the pressure read immediately and the voltmeter last. As soon as possible the electroscope was re-charged and the series of operations repeated. This gave a new pressure reading, by reason of the leak during the interval between the two observations. Five series of such observations were made and all observations plotted on the sheet. Through them a smooth curve B was drawn, and this curve corrected for leak. The following considerations enabled the correction to be made:

The pressure rises 5 cm. in ten minutes, or 5 mm. per minute. The time taken to note the discharge of the electroscope and read the manometer is approximately six seconds or one tenth minute. In this interval the pressure has risen 0.5 mm.—it is that much higher than it was at the instant the electroscope was discharged. The correction, then, is to shift the plotted curve to the left on the sheet through a distance corresponding to 0.5 mm. in pressure. Curve B', Fig. 2, results.

Special investigation was made to determine the influence of temperature variation on the corona-forming voltage. It was found that within the limits of variation of room temperature during observations (19° to 21° centigrade), such as influence is not appreciable.

Comment on Curves.

The intersection of the positive corona curves by the negative curves for the same wires is of the greatest interest. It has been suspected for some time that under certain circumstances the positive and negative coronas begin at different voltages. The difference varies with the size of wire and the pressure. In the case of each of the two wires for which observations of the negative corona were possible, there is a pressure below which the positive critical voltage is higher than the negative, while above this pressure the negative starts at the higher voltage.

The intimate relationship of the negative corona to the pressure and the size of wire is well shown in the curves. The 0.063 cm. wire forms a stable negative corona only at pressures above 25 mm. The 0.042 cm. wire gives a stable negative corona as low as 19 mm. This peculiarity of the negative corona has not, it is believed, been heretofore recorded.

The lower curve E_2 of Fig. 2 represents the observation that as the voltage is gradually lowered below that corresponding to the first deflection of the galvanometer needle, the negative corona persists for a time. The interval of voltage during which it continues to be observable on the galvanometer is indicated by the vertical lines.

E. A. Watson[1] has worked with the corona in cylindrical fields. He was able to use continuous potentials up to 70,000 volts, derived from an influence machine of special design. The wires used ranged in diameter from 0.070 cm. to 1.276 cm., and the pressure was varied from atmospheric down to 35 cm. He describes the same difference in the appearance of the two coronas as that observed here and finds that the negative corona starts at a higher voltage than the positive on the same wire. Watson found no region of pressure where the negative corona failed to appear.

V. Schaffers[2] has studied the continuous potential corona at atmospheric pressure, using extraordinarily small wires, 0.0003 cm. to 0.35 cm. He concludes that the ratio of the potentials critical for the positive and negative coronas varies regularly with the radius of the wire: for r = 0.01 cm. the two potentials are equal; for r less than this, the negative is lower than the positive; for r greater than 0.01 cm. the positive is the lower. These results refer to atmospheric pressure only, but tend to confirm Watson's observations and those of the present paper.

Investigators of the alternating corona have usually thought that the corona forms on the two half waves at the same value of instantaneous voltage. This conclusion is rendered doubtful by the experiments of

[1] Electrician, *63*, 828, 1909, and *64*, 707, 1910.

[2] Comptes Rendus, *157*, 203–206, 1913.

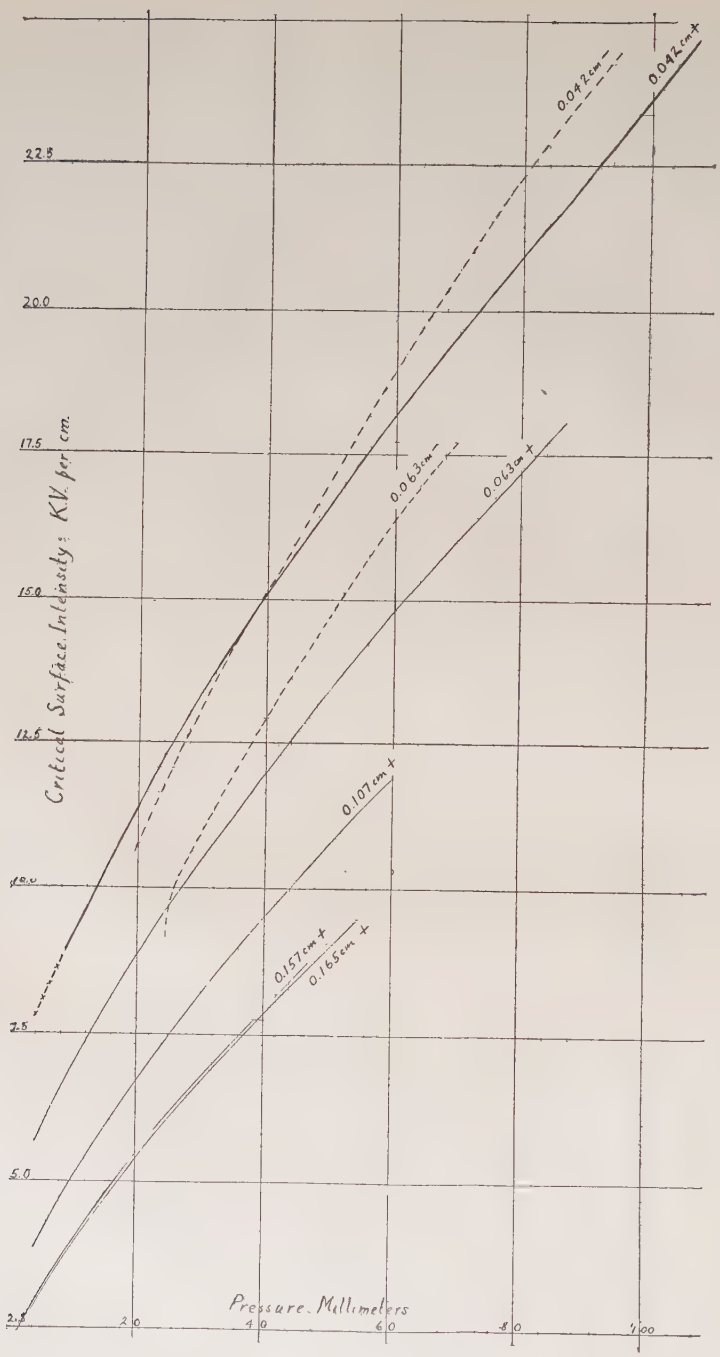

Fig. 3.

Critical surface-intensity. Solid curves indicate positive corona; dotted curves indicate negative corona.

Bennett,[1] who made an oscillographic study of the corona-current and voltage. When no corona discharge is taking place, the current oscillogram records only the charging current of the apparatus,—a pure sine wave. As the voltage is gradually raised to the critical value, the charging current recorded by the oscillograph remains a sine wave until the corona voltage is reached. At this point the charging current is broken by humps: a smooth hump for the positive corona, an oscillatory disturbance for the negative. Also the negative hump is more pronounced. This is in accord with the observations made here when using the galvanometer to detect the corona. It was found that the least perceptible deflection of the needle was a small fraction of a scale division for the positive corona; for the negative, however, the swing is through several scale divisions no matter how carefully the voltage is raised.

If it is true that one corona forms at a lower voltage than the other, then if the pressure and voltage are appropriate the corona tube should rectify the current due to an alternating potential. An experiment to test this was carried out with a 20 : 1 transformer, excited by 110 volts, 60 cycles. The pressure was adjusted to 85 mm. around the wire of 0.042 cm. diameter. This pressure corresponds for this wire to a positive critical potential lower than the negative. On closing the secondary circuit of the transformer and raising the voltage to the critical value, a steady deflection of the galvanometer needle occurs, corresponding to a positive current, *i. e.*, from wire to grounded cylinder. With increase in voltage the deflection is reversed: the negative current is larger than the positive. Thus the corona tube acts as a rectifier, the sign of the rectification depending on the value of the impressed voltage. No facilities were available for making a thorough investigation of the relation of galvanometer deflection and maximum value of the alternating voltage; it is hoped that this may be carried out in the future.

The above experiment was suggested by Dr. J. A. Anderson.

This was almost anticipated by an experiment of Dr. J. B. Whitehead.[2] In 1911 he reported to the American Institute of Electrical Engineers his observations of the ionization due to alternating currents in the corona tube. The method used was this: A woven wire cylinder was the grounded electrode, and was surrounded by a solid cylinder of metal connected through a D'Arsonval galvanometer to a source of continuous potential, the other D.C. electrode being grounded. At start of corona an excess of positive ions reaches the detector; at higher alternating potentials the excess is of negative charges. This should be interpreted

[1] Proceedings A. I. E. E., XXXII., 1473–1494, 1913.

[2] Ibid., XXX., 1857–1887, 1911.

to mean that the positive corona appears earlier, whereas when the negative corona is formed the ionization accompanying it is far more intense than that belonging to the positive half cycle. Dr. Whitehead, however, does not speak of the rectifying effect of the corona discharge: this would have been found had the galvanometer been in the A.C. circuit.

The theory of secondary ionization has been applied to the corona by Townsend.[1] His formula is verified by Watson's results. According two Tonsend

$$kv = P\left(30 + \frac{9}{\sqrt{aP}}\right),$$

where P is the pressure in atmospheres and a the wire diameter.

An empirical law has been proposed by Peek[2] to comprehend the results of work on pressure and temperature. His equation is

$$g = 31\delta\left(1 + \frac{.3}{\sqrt{r\delta}}\right),$$

where g = critical surface intensity in kilovolts per cm.,

r = radius of wire,

δ = "density factor," $= 3.92p/(273 + t)$: p is the pressure in centimeters, t is the temperature centrigade.

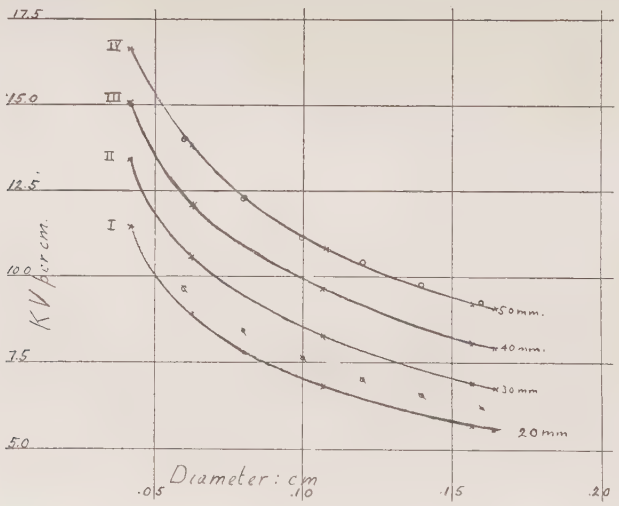

Fig. 4.

Critical surface-intensity and diameter of wire. Positive corona. Temp. = 21.°0 C. Circles indicate points plotted from Peck's law to compare with Curve III., $\delta = .0533$, $p = 4$ cm.; crossed circles indicate points plotted from Peck's law to compare with Curve I., $\delta = .0267$, $p = 2$ cm.

Electrician, 71, 348, 1913.

[2] Proceedings A. I. E. E., XXX., 1889–1963, 1911; XXXI., 1051–1092, 1912; XXXII., 1337–1355, 1913.

On Fig. 4 are plotted points derived from this equation for $t = 21$ degrees and $p = 2$ cm. and 4 cm.

The comparison shows that the computed curves differ from the observed numerically but not in form—the difference being a function of the pressure but independent of the diameter of wire. Further observations are necessary to enable a suitable correction term to be determined.

Transition points at various pressures are shown in Fig. 5 for two wires. At the left in Fig. 5 is the curve of transition point for the positive corona,

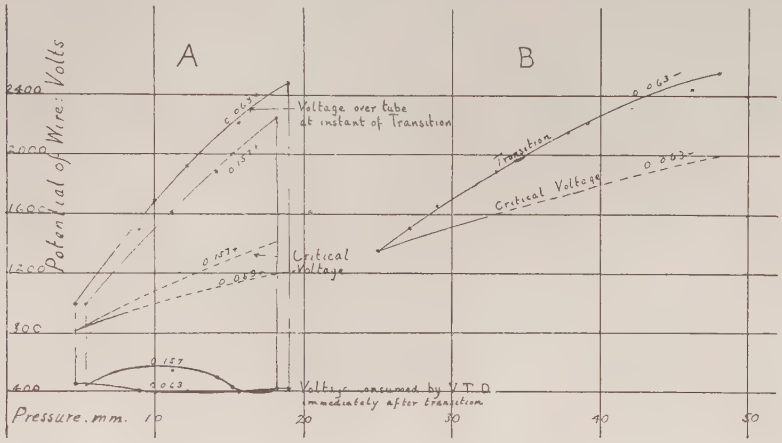

Fig. 5.

Voltage of transition from corona to vacuum-tube discharge. *A*, Positive effect, wires of diameter 0.157 cm. and 0.063 cm.; *B*, Negative effect, 0.063 cm. wire. Critical voltages shown in dotted curves.

at the right that for the negative. The straight vertical lines in the positive figure represent the instantaneous drop in tube-wire voltage attendant upon the transition from corona to vacuum-tube discharge,—no such observations were made in the work on the negative corona. The ordinates of the upper curve are the voltages at which transition occurs; those of the lower curve are the voltages consumed by the vacuum-tube discharge immediately after the transition. The critical voltages are shown in dotted curves.

In the case of the negative wire at pressure 24.5 mm. the curve of transition point intersects the curve of critical voltage. At this pressure the range of the negative corona on this wire is so narrow as to be within the voltage fluctuations. The observations do not establish such a point for the positive corona.

Conclusion.—It seems unprofitable to speculate on the nature of the corona until it has been more thoroughly studied. Observations at

atmospheric pressure and at pressures considerably below the atmosphere have yielded empirical equations which require modification to enable them to include the results reported in this paper. The ionization current which in the case of small wires exists before the luminous discharge begins, the transition from corona to vacuum-tube discharge, the dependence of the stable negative corona on the wire size and on the pressure,—all these questions call for extended investigation.

The principal results of the work described in this paper may be briefly enumerated as follows:

1. The formation of the stable negative corona has been shown to be dependent upon the pressure and the size of conductor. Of the wires used, with those of larger diameter such a corona is never formed, while around the smaller wires the negative corona can exist only at pressures greater than a critical value which varies with the diameter of the wire.

2. The transition has been observed from the stable corona to the vacuum-tube discharge. The vacuum-tube discharge is the only luminous discharge with negative wires below the critical pressure.

3. Curves have been plotted of critical surface intensity for the positive corona and wire diameter at various pressures. These curves are similar in form to those of Peek's equation

$$g = 31\delta\left(1 + \frac{.3}{\sqrt{r\delta}}\right).$$

Values calculated from this equation differ from those observed by a quantity which is a function of the pressure but independent of the diameter of the wire. The observations are not sufficiently numerous to determine the correction to the formula.

4. The ratio of the critical voltages for the positive and negative coronas on a given wire varies with the pressure. A pressure exists at which the two critical voltages are equal; below this pressure the negative critical voltage is lower than the positive, at higher pressures the positive corona-forming voltage is the lower.

5. The corona rectifies an alternating current, the direction of the rectified current depending on the voltage and the pressure.

6. In the case of the smallest wire evidence has been found of the existence of an ionization current flowing before the appearance of the luminous discharge.

It is a pleasure to acknowledge the indebtedness I am under to those who have assisted me in this undertaking. The work was begun at the suggestion of Dr. J. B. Whitehead, and his published papers have been

constantly consulted. My particular thanks are due to Professor Ames, who has aided and encouraged the work in every possible way. Valuable assistance has been received from Dr. J. A. Anderson and Mr. M. W. Pullen. I am grateful as well to my fellow student, Mr. S. M. Burka, for his kindness in the matter of glass-blowing and to Mr. Frank Smith for his careful mechanical work.

JOHNS HOPKINS UNIVERSITY,
BALTIMORE, May, 1914.

VITA.

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